LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

LLNL-JRNL-410873

Differential Spectroscopic Measurements at Electron Beam Ion Traps

E. Träbert

February 26, 2009

Journal of Physics B: Atomic, Molecular and Optical Physics

Disclaimer

Differential spectroscopic measurements at electron beam ion traps

E Träbert

Astronomisches Institut, Fakultät für Physik und Astronomie, Ruhr-Universität Bochum, D-44780 Bochum, Germany,
and
Physics Division, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

E-mail: traebert@astro.rub.de

Abstract. In many atomic physics experiments in an electron beam ion trap, the technical system is used to provide a cloud of highly charged ions which are then probed for properties such as excitation energies or magnetic sublevel population (via the polarization of the emitted light). However, there also are observations in which electron beam properties or ion trapping conditions are systematically varied to obtain atomic properties, as well as measurements of the changes over time of the stored ions, their atomic states and their ensemble properties.

Submitted to: *J Phys B: At. Mol. Opt. Phys.*

PACS numbers: 3270Cs, 3230Jc, 3210Fn

1. Introduction

Ion traps are marvellous tools for a great variety of atomic physics experiments. Probably, the majority of such traps are being used for singly charged ions that can be interrogated by laser light. Electrostatic (Kingdon) and magnetic (Penning) ion traps have also been used to store multiply charged ions, as have radiofrequency (Paul) traps. Apparently more suitable to the task is, however, the electron beam ion trap [1] which can be seen as a Penning trap with a built-in electron beam that helps with producing highly charged ions inside the trap and - via space charge effects - with the trapping of the ion cloud. (A relativistic electron beam can trap an ion cloud even without an external magnetic field [2].)

If one switches off the electron beam after making a cloud of highly charged ions, the positively charged ion cloud significantly expands, but remains confined in the Penning trap [3]. When the electron beam is switched on again, the old ion cloud does not contract to its former small size, but a new one is produced along electron beam. The electron density in the electron beam is much higher than the ion density in the same

volume, although (because of space charge compensation) the ion density can be much higher than without the beam. A plasma with a net negative charge is thus produced on the axis (defined by the electron beam) of the previously produced positive ion cloud. Evidently, these are non-neutral plasmas, and a plethora of plasma dynamical experiments should be possible with them (see [4] and the conference proceedings that paper was part of).

However, such plasma dynamics are not what I want to discuss here, but other dynamic processes and information that can be gained differentially from changing the running conditions of an electron beam ion trap, in particular the energy and/or the current of the electron beam. This goes beyond the standard staple experiment performed at practically all EBITs in which the electron beam energy is swept through a range of values to find the position of dielectronic recombination (DR) resonances and radiative recombination (RR) processes which are detected through X-ray emission ([5], see also reviews in [6]). Instead, I am discussing atomic properties that can be measured or at least inferred from an electron beam modulation experiment and which may influence the dynamics of a plasma. Such entities are atomic lifetimes, the identification of charge states in atomic spectra, and the response of charge state distributions to changes in external parameters because of the finite atomic lifetimes of metastable levels.

The electron beam in an EBIT serves to ionize itinerant atoms of the residual gas in the ultrahigh vacuum (UHV) vessel or of a ballistically injected gas plume (still at UHV particle densities) so that they can be trapped by the electric potential difference of collinear drift tubes and axially confined by a strong (several Tesla) magnetic field. Instead of starting from neutral atoms, one can inject ions in low charge states from an external ion source, for example a Metal Vapour Vacuum Arc (MeVVA) source, that drift along the magnetic field into the trap volume. The ions will mostly be confined to the volume of the electron beam, and there they can be hit again and again. Further ionization stops when the next step would require to overcome an ionization potential higher than the electron beam energy (an exception is being discussed below). The actual charge state balance in the ion cloud depends on ionization and recombination processes with energetic beam electrons or by charge exchange (CX) with neutral particles of the residual gas. Under clean enough vacuum conditions, a 200 keV electron beam can fully ionize uranium and reach U^{92+} ions [7]. Hence ions of all charge states of all elements can be produced. The highest charge state produced can be selected by external parameters. This tool can be exploited for the separation of complex spectra of consecutive charge states of a given element (section II).

Most ions will be in their ground state, because the cross sections for excitation are small for collisions with energetic electrons, and the electron density in the beam is still rather low for any laboratory plasma, in the range near $n_e = 10^{11}\,\mathrm{cm}^{-3}$. The collision rates are lower than most radiative rates, and the ions usually have time to return to the ground state or a low-lying metastable level before they are being hit again. Consequently, the EBIT spectra are dominated by the decays of levels that can

be excited from the ground state directly. This is in stark contrast to the interaction of fast ions with a thin foil target (solid state density) [8]. Some other levels may be populated as a consequence of recombination or CX. Drastic changes in the level population after CX have been observed at very low collision energies (sub-keV to eV); such low energy CX collisions of highly chrged ions with neutral gas atoms are being discussed as the source of X-ray emission from comets [9].

An important point to recognize about EBIT is that all excitation stops when the electron beam is switched off. CX processes continue, and radiative decays take place, but ionization and collisional excitation by swift electrons end. A steady state dynamic balance thus is replaced by non-equilibrium conditions. This offers a window into measuring time-dependent process such as the radiative decay of metastable levels (section III).

It is not always necessary to switch the electron beam off. It is also possible to vary the electron beam energy and current in order to simulate a Maxwellian electron energy distribution [10], or to change in a controlled manner between two settings and the associated steady-state conditions. Out of the multitude of possible experiments, I will present one in which atomic properties visibly influence the transition to a new steady state equilibrium (section IV).

2. Charge state analysis of spectra

A persistent problem in spectral analysis is the determination not only of the element that is emitting a given spectral feature, but also the charge state, before it makes sense to assign a transition. The historic path has been the intercomparison of spectra recorded at a flame, an arc, or a spark, but this covers only the first few ionization stages. If one changes the parameters of a spark discharge, one changes the charge state distribution, but has no information by how much. The same holds true for fast ion beams in beam-foil spectroscopy, or laser-produced plasmas. In contrast to this, the electron beam energy in an electron beam ion trap can be adjusted in a very controlled way, steering for a defined maximum charge state. Certain problems arise from the energy width of the beam, which is usually between 30 and 50 eV, space charge effects, and contact potentials. For relatively low charge states, the ionization potentials may differ by less than the energy width of the electron beam. However, if done carefully, spectra recorded at selected electron beam energy may differ by the contributions of a single charge state. The difference spectra then may represent the spectral information from that single charge state spectrum.

This technique has been demonstrated at Livermore (among other cases) for the extreme ultraviolet (EUV) spectra of Fe^{7+} to Fe^{9+}, Ar^{8+} to Ar^{15+}, and S^{6+} to S^{13+} [11, 12, 13]. At the Tokyo EBIT laboratory, a small EBIT has been built for applications in astrophysics. With this device, the next higher charge states of Fe have recently been studied in the same way [14, 15]. The Japanese group used a flat-field EUV spectrometer basically similar to the Livermore equipment, and also a CCD camera. In this way,

the difference spectra become available by channel-by-channel subtraction of spectral recordings that each have about 1000 to 1300 data channels spanning a spectral range from, say, 3 to 10 nm or from 8 to 20 nm. In such a range, some 30 to 100 spectral lines are seen, both in EBIT and in spectra recorded on board of spacecrafts such as *Chandra* or $XMM-Newton$ pointing at astrophysical objects in outer space. Of these, many arise from Fe ions (because of the high cosmic abundance of Fe), and some two to 15 lines can typically be identified with a specific charge state.

3. Atomic lifetime measurements

Not only is the highest charge state reached in an EBIT limited by the electron beam energy, in two-electron ions (He-like spectrum), the lowest triplet level, $1s2s\ ^3S_1$, has a higher excitation energy than the ionization energy of the next lower charge state, the three-electron ion (Li-like spectrum). The magnetic dipole (M1) decay of this level is described by a purely relativistic operator. The line ('z' in plasma physics parlance) is prominent in many low density plasmas and it plays a role in plasma diagnostics. The line was first recognized in solar X-ray spectra [16] against the theoretical verdict by George Breit and Edward Teller [17] that the transition could not happen by a single photon decay. By now, the rate of this transition has been measured from He (Z=2) to Xe (Z=54), finding an upper level lifetime that varies by 15 orders of magnitude over this range. Beam-foil spectroscopy has targeted this transitions with measurements from Z=16 upward. In the higher-Z part of the range (picosecond lifetimes), the results scatter by up to 10% around the predicted trend, but near Z=18 (Ar), the experimental error of the many-hundred nanosecond lifetimes initially was deceptively low, while the results differed massively from expectation. Certain oversights in the early experiments have been recognized meanwhile and the discrepancies removed. However, it was an important step when work at the TSR heavy-ion storage ring at Heidelberg and at the Livermore EBIT not only extended the lifetimes covered to the millisecond and eventually second range, but did so with an accuracy of one percent and better (see general discussions in [18, 19]).

The first EBIT experiment of the series was on Ne^{8+} [20]. In this study, the electron beam energy was modulated to alternate between values just above the excitation energy of the level of interest and a value below, which would nevertheless maintain the same charge state balance. The X-ray signal of the $1s2s\ ^3S_1$ proved to be a clean single exponential. In later experiments [21], the beam was simply shut down completely after ion production and for the duration of the photon observation. This brings about the complication of a possible change of the charge state composition in the trap, but that is not causing any notable error. In fact, when studying the radiative decay of an ion sample, it is necessary to monitor the number of ions in the ion cloud, which might get lost due to diffusion out of the observation volume or by charge exchange. Such monitoring is more straightforward without ane electron beam that tries to restore the previous steady state balance. If the vacuum is good enough, CX observations have

shown an ion loss rate from the trapped ion sample that corresponds to storage time constants of many seconds. This ion loss is then a minor correction to the raw lifetime data of milli- or microsecond radiative lifetimes.

At Livermore, atomic lifetime measurements of metastable levels in various ions by now range from many nanoseconds [22] to many milliseconds [23]. The claimed measurement accuracy has reached 0.1% in several experiments at the Heidelberg EBIT [24, 25]. At this level of uncertainty, the results are at variance with complex quantum mechanical calculations that include QED not only in the energy levels, but also in the M1 transition operator. However, recent experiments at the Heidelberg heavy-ion storage ring suggest that the accuracy may have been overstated [26]. Even then a discrepancy remains that needs to be resolved.

Most of the atomic lifetime measurements concern M1 or M2 transitions. At the heavy-ion storage ring, some E2 transition rates have been measured as well, and at the Livermore EBIT, the highest multipole order decay studied has been a magnetic octupole decay (M3) as it occurs in Ni-like ions [27]. Xenon, however, has a number of isotopes, and odd ones among them. Measurements on individual isotopes quantitatively have confirmed a theoretical suggestion that the hyperfine interaction should mix E2 and M3 decays in this case [28], and thus certain sublevels show a shorter lifetime.

One motivation for such lifetime measurements is the intellectual quest of finding out whether quantum mechanics can be implemented well enough in the description of many-electron systems that in the combination with QED the results are experimentally testable to high precision. If discrepancies persisted, they might indicate physics beyond the Standard Model, and radiative lifetime calculations with their set of operators differing from those in atomic structure calculations might harbour surprises. Another, more 'applied' interest is in the benchmarking of extensive collisional-radiative codes that are used to describe terrestrial and astrophysical plasmas. The codes comprise thousands or ten thousands of levels and ten times as many transitions. The energies of some levels may be known from measurements; the lifetimes of some low-lying levels with E1 decays may be roughly known from beam-foil or laser spectroscopic studies. Such detail almost vanishes in the complexity and richness of the models. However, the states in the ground configuration usually decay towards the true ground state by M1 or E2 transitions, with level lifetimes in the millisecond range. In low-density plasmas, the radiative decays compete with collisional excitation, with significant changes in the relative level population of those very low lying levels as a function of density and a notable effect on certain line intensity ratios. Incidentally, these lifetimes of low-lying levels can often be measured at a heavy-ion storage ring or in an EBIT, and they may be the best parameter that an experiment can test for the modeling, and thus validate some part of such a calculational model.

4. Dynamic effects in plasmas

In spectroscopic observations of a plasma it is usually assumed that most variations of a plasma are happening much faster than the interrogation time. However, metastable levels of certain ion species have an influence on various balances in a plasma, for example the polulation distribution or the charge state distribution. Under steady-state conditions, this role may be modeled and inferred; if one perturbs the plasma towards a nonequilibrium state, the role may be directly measurable.

I take as an example the $3d^9 4s\ ^3\mathrm{D}_3$ level of Ni-like ions. This is the lowest excited level, and its only decay channel to the $3d^{10}\ J = 0$ ground state is by a magnetic octupole (M3) transition as mentioned above. When the charge state distribution in a hot Au plasma was modeled, there were clear discrepancies between expectations supported by HULLAC code radiative-collisional modeling and actual experimental data, until the role of the long-lived $3d^9 4s\ ^3\mathrm{D}_3$ level in Ni-like ions was recognized [29]. Such a special role (see below) was even explicitly denied for this level in the electron excitation calculations by Badnell *et al* : the level was intentionally excluded [30].

In a sequence of increasing charge state q+ of a given element, the ionization energy is a monotously increasing function, defined as the energy necessary to remove a valence electron from one ion by exciting it to the ionization limit of the next higher charge state ion, which is in its ground state. For the Cu-, Ni-, and Co-like ions of Xe this means values of about 0.86, 1.50, and 1.58 keV. An electron beam of energy below 1.5 keV would not be expected to ionize the Ni-like ion Xe^{26+}, but an electron beam of not much more than this threshold value could ionize both, Xe^{26+} and Xe^{27+} (Co-like), ions. Measurements at the Livermore EBIT have determined an excitation energy of 590 eV for the $3d^9 4s\ ^3\mathrm{D}_3$ level of Ni-like Xe ions [31]. If a Xe^{26+} ion is excited to this level, it shows a radiative level lifetime of about 15 ms [27] (neglecting hyperfine effects). Another electronic excitation of at least 910 eV can ionize the Ni-like ion further, as long as the ion is in the excited state. That means, the metastable level provides a stepping stone, and the effective ionization threshold is lowered from 1.50 keV to merely 0.91 keV. This more than a curiosity on paper: in observations at Livermore, the (Co-like) spectrum of Xe^{27+} [32] was indeed produced [33] with an electron beam energy well below the 1.5 keV value of the standard definition of an ionzation potential (figure 1). When the electron beam is switched on at the beginning of a trapping cycle, the ions of the various charge states are sequentially produced. By the energy argument, the Co-like ion should be produced as soon as there are any Ni-like ions. However, a time delay seems to indicate that the ionization towards the Co-like ion requires notably more time - which may be seen as evidence for ionization through a multistep pathway of limited phase space. (We are working on a simulation of the time dependence of the spectra [34].) Hence individual atomic levels can have a notable influence on the rate with which a plasma adjusts to changes of external conditions.

5. Conclusions

Electron beam ion traps have had a remarkable career as sources of ions that could either be kept trapped (and studied) or ejected as a beam in order to serve collision studies. The capabilities of the device, however, are far from exhausted. Recent applications have used the ions in an EBIT as a multi-line x-ray source for measurements of x-ray filter transmission data [35], and the study of internal dynamics of the trapped ion cloud and of the ion plasma response to perturbations is only just beginning.

Acknowledgments

This discussion draws on experiences from more than a decade of collaboration with the Livermore EBIT group, the hospitality of which is greatly appreciated. ET acknowledges travel support by the Deutsche Forschungsgemeinschaft (DFG). Some of this work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

References

[1] Levine M A, Marrs R E, Henderson J R, Knapp D A and Schneider M B 1988 *Phys. Scr.* T **22** 157
[2] Kleinod M, Becker R, Höltermann H, Mücke M, Rao R, Weidenmüller M and Zipfel B 1998 *Rev. Sci. Instrum.* **69** 718
[3] P. Beiersdorfer, L. Schweikhard, J. Crespo López-Urrutia, and K. Widmann, Rev. Sci. Instrum. **67**, 3818 (1996).
[4] Schweikhard L, Beiersdorfer P and Träbert E 2002 in *Non-neutral plasma physics IV: Proc. 2001 Int. Workshop on Non-neutral Plasmas*, San Diego (CA, USA), edited by F Anderegg, C F Driscoll, and L Schweikhard, *Am. Inst. Phys. Conf. Proc.* **606** 174
[5] Knapp D A, Marrs R E, Schneider M B, Chen M H, Levine M A and Lee P 1993 *Phys. Rev.* A **47** 2039
[6] Beiersdorfer P *Can. J. Phys.* **86** 1
[7] Knapp D A, Marrs R E, Elliott S R, Magee E W and Zasadzinski R 1993 *Nucl. Instrum. Meth. Phys. Res.* A **334** 305
[8] Träbert E, Beiersdorfer P, Pinnington E H, Utter S B, Vilkas M J and Ishikawa Y 2007 J. Phys. Conf. Ser. **58** 93
[9] Beiersdorfer P, Boyce K R, Brown G V, Chen H, Kahn S M, Kelley R L, May M, Olson R E, Porter F S, Stahle C K and Tillotson W A 2003 *Science* **300** 1558
[10] Savin D W, Beck B, Beiersdorfer P, Kahn S M, Grown G V, Gu M F, Liedahl D A and Scofield J H 1999 *Phys. Scr.* T **80** 312
[11] Lepson J K, Beiersdorfer P, Brown G V, Liedahl D A, Utter S B, Brickhouse N S, Dupree A K, Kaastra J S, Mewe R and Kahn S M 2002 *Astrophys. J.* **578** 648
[12] Lepson J K, Beiersdorfer P, Behar E and Kahn S M 2003 *Astrophys. J.* **590** 604
[13] Lepson J K, Beiersdorfer P, Behar E and Kahn S M 2005 *Astrophys. J.* **625** 1045
[14] Sakaue H A, Kato D, Nakamura N, Watanabe E, Yamamoto N and Watanabe T 2008 *Abstract B-a01, Int. Conf. Highly Charged Ions HCI-2008*, Chofu (Japan)
[15] Yamamoto N, Sakaue H A, Kato D, Murakami I, Kato T, Nakamura N, Watanabe E and Watanabe T *Abstract B-a04, Int. Conf. Highly Charged Ions HCI-2008*, Chofu (Japan)
[16] Gabriel A H and Jordan C 1969 *Nature* **221** 947

[17] Breit G and Teller E 1945 *Ap. J.* **91** 215
[18] Träbert E 2002 *Can. J. Phys.* **80** 1481
[19] Träbert E 2008 *Can. J. Phys.* **86** 73
[20] Wargelin B J, Beiersdorfer P and Kahn S M 1993 *Phys. Rev. Lett.* **71** 2196
[21] Träbert E, Beiersdorfer P, Brown G V, Smith A J, Utter S B, Gu M F and Savin D W 1999 *Phys. Rev.* A **60** 2034
[22] Crespo López-Urrutia J R, Beiersdorfer P and Widmann K 2006 *Phys. Rev.* A **74** 012507
[23] Träbert E, Beiersdorfer P, Gwinner G, Pinnington E H and Wolf A 2002 *Phys. Rev.* A **66** 052507
[24] A. Lapierre, J. R. Crespo López-Urrutia, J. Braun, G. Brenner, H. Bruhns, D. Fischer, A. J. González-Martínez, V. Mironov, C. J. Osborne, G. Sikler, R. Soria Orts, H. Tawara, J. Ullrich, V. M. Shabaev, I. I. Tupitsyn, and A. Volotka, Phys. Rev. A **73**, 052507 (2006).
[25] Brenner G, Crespo López-Urrutia J R, Harman Z, Mokler P H and Ullrich J 2007 *Phys. Rev.* A **75** 032504
[26] Träbert E, Hoffmann J, Krantz C, Wolf A, Ishikawa Y and Santana J A 2008 *J. Phys. B: At. Mol. Opt. Phys.* (to be published)
[27] Träbert E, Beiersdorfer P and Brown G V 2007 *Phys. Rev. Lett.* **98** 263001
[28] Yao K, Andersson M, Brage T, Hutton R, Jönsson P and Zou Y 2006 *Phys. Rev. Lett.* **97** 183001; erratum 2007 *Phys. Rev. Lett.* **98** 269903
[29] May M J, Fournier K B, Beiersdorfer P, Chen H and Wong K L 2003 *Phys. Rev.* E **68** 036402
[30] Badnell N R, Berrington K A, Summers H P, O'Mullane M G, Whiteford A D and Ballance C P 2004 *J. Phys. B: At. Mol. Opt. Phys.* **37** 4589
[31] Träbert E, Beiersdorfer P, Brown G V, Terracol S and Safronova U I 2005 *Nucl. Instrum. Meth. Phys. Res.* B **235** 23
[32] Träbert E, Beiersdorfer P and Gu M F 2008 *Can. J. Phys.* **86** 467
[33] Träbert E, Beiersdorfer P, Brown G V, Gu M F and Hansen S B 2008 (work in progress)
[34] Träbert E, Brown G V, Gu M F and Hansen S B (work in progress)
[35] Brown G V, Beiersdorfer P, Emig J, Frankel M, Gu M F, Heeter R F, Magee E, Thorn D B, Widmann K, Kelley R L, Kilbourne C A and Porter F S 2008 *Rev. Sci. Instrum.* **79** 10E309

Figure captions

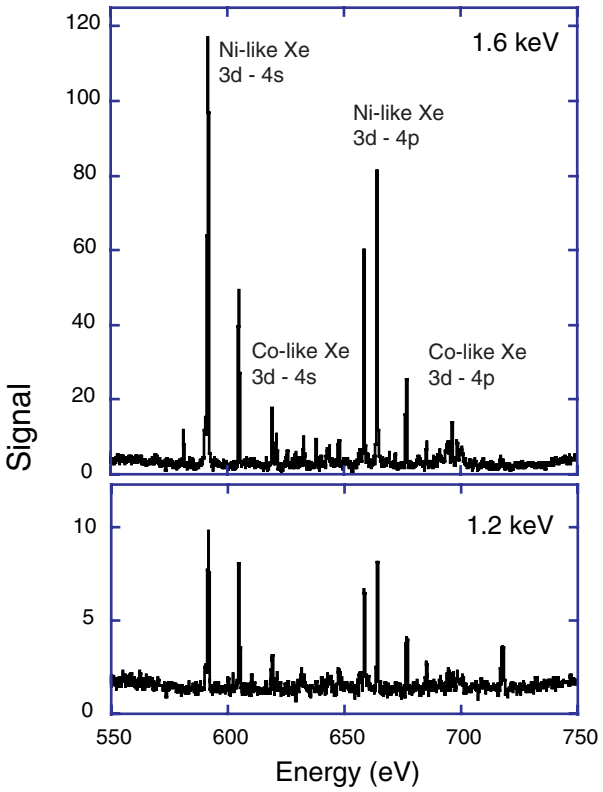

Figure 1. Lines typical for Xe XXVIII (Co-like Xe^{27+} ions) are seen to be produced at an electron beam energy of 1.2 keV, well below the 1.5 keV ionization potential of Xe XXVII (Ni-like Xe^{26+} ions).